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A review of surface engineering issues critical to wind turbine performance

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Abstract

Wind turbine performance can be significantly reduced when the surface integrity of the turbine blades is compromised. Many frontier high-energy regions that are sought for wind farm development including Nordic, warm-humid, and desert-like environments often provide conditions detrimental to the surface of the turbine blade. In Nordic climates ice can form on the blades and the turbine structure itself through a variety of mechanisms. Initial ice adhesion may slightly modify the original aerodynamic profile of the blade; continued ice accretion can drastically affect the structural loading of the entire rotor leading to potentially dangerous situations. In warmer climates, a humid wind is desirable for its increased density; however, it can come at a price when the region supports large populations of insects. Insect collisions with the blades can foul blade surfaces leading to a marked increase in skin drag, reducing power production by as much as 50%. Finally, in more arid regions where there is no threat from ice or insects, high winds can carry soil particles eroded from the ground (abrasive particles). Particulate-laden winds effectively sand-blast the blade surfaces, and disrupt the original skin profile of the blade, again reducing its aerodynamic efficiency. While these problems are challenging, some mitigative measures presently exist and are discussed in the paper. Though, many of the current solutions to ice or insect fouling actually siphon power from the turbine itself to operate, or require that the turbine be stopped, in either case, profitability is diminished. Our survey of this topic in the course of our research suggests that a desirable solution may be a single surface engineered coating that reduces the incidence of ice adhesion, insect fouling, and protects the blade surface from erosive deterioration. Research directions that may lead to such a development are discussed herein.

Keywords: Wind energy; Surface engineering; Turbine icing; Insect fouling; Blade surface erosion; Materials science

Contents

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Nomenclature

d	projected distance of ice throw
D	diameter of turbine rotor
H	height of nacelle
W_A	the work of adhesion

Greek symbols

γ_1	surface energy per unit area of material 1
γ_2	surface energy per unit area of material 2
γ_{12}	surface energy per unit area of interface between materials 1 and 2
γ_{lv}	surface energy per unit area of interface between liquid and vapor
θ	contact angle

1. Introduction

Wind energy is a renewable power source that produces no known significant atmospheric pollution. Currently the world-wide capacity of installed wind energy stands at more than 40,000 MW with a 30% growth rate predicted over the next decade. Maintaining such growth necessitates research into the management of economic and environmental risks associated with the operation of large-scale commercial wind ventures. Wind turbine technology has a unique technical identity and subsequently has unique demands in terms of methods used for design [1]. A focal variable critical to the economic optimization of wind power production is the evolution of the wind turbine blade. Fundamental to the efficient extraction of power from the wind are the structural and aerodynamic properties of the blade. Until relatively recently it was enough to design blades with a desirable aerodynamic profile and a durable yet responsive structure. However, with the expansion of wind infrastructure, an increasing number of turbine installations have pushed their way into three distinct climatic zones, icy Nordic environments, humid regions that support large insect populations, and desert environments with sand-laden winds. Each of these environments can create significant operational issues for a wind farm; critical to the comprehension and potential resolution of all three issues are the composition, specifically the surface properties of the turbine blade. Currently, most manufacturers employ epoxy or polyester matrix composites reinforced with glass and/or carbon fibres; though polyester and glass fibres remain the material of choice due to their lower capital cost, despite the superior mechanical properties of epoxy and carbon fibres. A compatible gelcoat is also typically applied on the finished blade to improve surface erosion resistance. The wind energy industry presently faces three major challenges concerning the surface engineering of blades: ice adhesion and accretion on the turbine blades and supporting structure, insect accumulation on blades, and the erosion of blades by sand and water droplets. We have yet to uncover much literature that addresses the surface engineering issues facing wind turbines in a holistic sense. This is likely due to the complexity associated with a multidisciplinary challenge that calls on expertise from materials science, aero-, thermo-, and structural-dynamics. We endeavour to provide details of the current challenges confronting the industry, then discuss present solutions, and propose potential research directions.

2. Effects of icing

Wind turbines installed in cold climates face icing issues over their service life. Ice accretion on wind turbines, particularly turbine blades, can be detrimental to turbine

performance, durability, and the safety of those in the vicinity of operating iced turbines. In the following sections the issues with icing, ice adhesion, and accretion in cold weather are discussed.

2.1. Problems due to icing

Prior to addressing causes and measures of mitigation, the significant problems icing causes commercial wind generation are discussed.

2.1.1. Full stop of the turbine

In some cases, severe icing has led to the complete stop of the turbine—resulting in significant energy loss. This is the simplest of all loss mechanisms to quantify, and certainly an event all operators wish to avoid at nearly any cost. The Äppelbo wind turbine in Sweden, for example, reported 7 weeks of turbine stoppage in the winter of 2002–2003. The Swedish statistical incident database contains a total of 1337 such 'stop' records reported to have occurred between 1998 and 2003—resulting in a total downtime of 161,523 h. Ninety-two of the incidents (7%) were related to the cold climate and resulted in 8022 h (5%) of production loss. The reported low-temperature downtime for all cold climates was 669 h (8%) while the equivalent for icing events was 7353 h (92%). Downtimes reported due to icing in Finland between 1996 and 2001 resulted in 1208, 495, 196, 581, 739 and 4230 h for 19, 21, 29, 38, 61 and 61 turbines, respectively [2].

2.1.2. Disruption of aerodynamics

Antikainen and Peuranen [3] performed a comprehensive study of the effects of icing time and shapes on the aerodynamic balance of turbine blades, and the results suggested that both mass and aerodynamic imbalance can occur even in the early stages of icing. Jasinski et al. [2] established that even the onset of ice accretion could cause a slight increase in surface roughness that, in turn, increases the drag coefficient—reducing power production. Field data, wind tunnel simulations and numerical analyses have been used to describe the ice formation on wind turbine blades, as well to calculate the aerodynamic coefficients and power curves for iced wind turbines and study the corresponding loads. Ice accretion on blades nearly always decreases power production, and at harsh sites the annual power loss is typically in the range of 20–50% [4].

2.1.3. Overloading due to delayed stalls

Jasinski et al. [2] demonstrated that under certain conditions, stall regulated wind turbines that develop ice accretion experienced a temporary increase in power production as a consequence of delayed stalling. Though ice accretion typically reduces airfoil efficiency, the rime ice that had formed on the blades assumed the shape of a leading edge flap. This subsequently was postulated to increase the maximum lift coefficient and delayed aerodynamic stall to a higher angle of attack. As a result, maximum power development increased beyond typical limits. Though seemingly desirable, this has a long-term detrimental effect on generator and blade mechanical health. It was also conceded that the increase in power may have been strictly due to the increased air density associated with the cold icing temperatures.

2.1.4. Decreased fatigue life

The operation of a wind turbine with an imbalance caused by icing experiences an increase in the loads imposed on all turbine components. Although the extreme loads are treated at the design level, the fatigue loads will shorten the lifetime for the components [4,5]. Details of these effects were illustrated in the WECO (Wind Energy Production in Cold Climates) project [6]. They found the following:

- Additional ice masses will cause higher deterministic loads.
- Asymmetric masses will cause unbalance.
- Ice accretion will increase the excitation of edgewise vibrations.
- Resonance may occur due to the changed natural frequencies of the blades, particularly for smaller turbines and light-weight rotor blades.

2.1.5. Human safety risks

Ice thrown from rotating blades poses a serious safety issue, particularly when the wind power plant site borders public roads, housing, power lines, and shipping routes. Ice throw has been studied using both theoretical models and collected experimental data, such as questionnaires sent to operators in various parts of Europe and observations made at the WECO test sites [6]. These studies have prompted a recommendation that for sites with a high probability of icing, the distance between the turbine and the nearest object should adhere to the following equation—with the effect of slopes taken into account for mountainous sites:

$$d = 1.5(D + H) \quad (1)$$

where d is the projected distance ice can be thrown, D is the diameter of the rotor and H is the height of the nacelle. This equation should be considered a rough estimate, but it provides a general idea of the area at risk [6,7].

2.2. Wind turbine performance in cold weather

In spite of all the difficulties mentioned above, there exists increasing interest in cold-climate wind turbines. Air density variations affect the power output of wind turbines, and based on the equation of state for an ideal gas, air at $-30\,^{\circ}\mathrm{C}$ is 26.7% denser than at $35\,^{\circ}\mathrm{C}$. Power is proportional to air density; accordingly the power output increases at low temperatures [8], and the higher energy output has sparked an increasing interest in sites at both higher altitude and latitude—despite the limitations caused by harsh weather conditions. There are three major concerns when operating in cold weather:

- Impact of low temperatures on the physical properties of materials.
- Ice accretion on structures and surfaces.

- The presence of snow in the vicinity of a wind turbine [6].

Ice accretion represents the most significant threat to the integrity of wind turbines in cold weather. The amount and type of accreted ice depends on a variety of factors such as climate condition, the shape and kind (stationary or moving) of the turbine component subjected to icing and the surface characteristics of the component. Fig. 1 illustrates an example of ice accretion on a wind turbine blade in Germany.

2.2.1. Icing types (ice formation)

Different kinds of icing occur at different sites, the two main types of ice accumulation being in-cloud icing and precipitation icing [9,10]. Frost, a third method of ice accumulation, is not believed to cause any problems for wind turbines. The two main categories can be further subdivided from in-cloud icing into rime or glaze ice; and precipitation ice can be further subdivided as wet snow or freezing rain variants.

2.2.2. In-cloud icing

In-cloud icing occurs with the impact of super-cooled droplets on a surface. Super-cooled droplets appear in clouds with ambient temperatures of -20 to $-35\,^{\circ}\mathrm{C}$ [11]. These droplets freeze on surface contact. The temperature and size of the droplets determines whether the ice formed will be considered hard rime, soft rime, or glaze [2,6]. Rime is formed when super-cooled droplets impact the surface and the thermal energy released is removed quickly enough by wind and radiation such that no liquid water is present on the surface. Rime ice is white, and breaks off more easily than glaze. Soft rime forms when the droplet size is small and the water content in the air is low. It has a lower density than hard rime, due to larger air gaps between the frozen particles. Likewise, hard rime forms as a result of medium-sized droplets with higher water content in the air; subsequently, it is harder largely due to better bonding and smaller air gaps between the frozen particles [7,9,10].

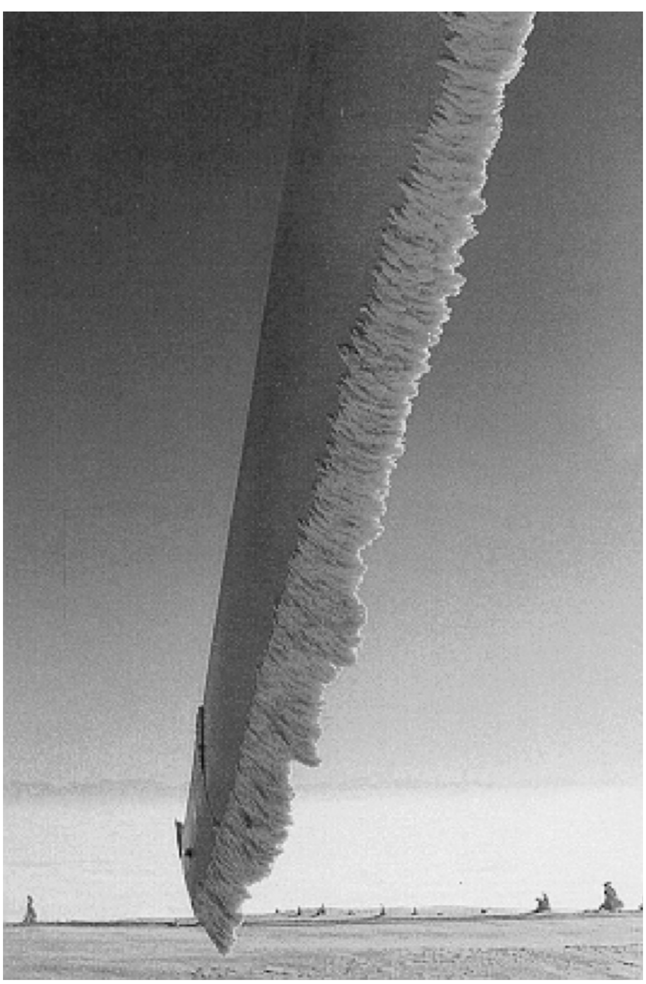

Fig. 1. Iced turbine blade in Switzerland; Tammelin et al. [6] (Photo by ADEV).

Glaze is formed when the thermal energy released during droplet surface impact is not removed as quickly as it is for rime, and some portion of the droplets remain as liquid water. As the amount of trapped air is very low, glaze is a solid cover of clear ice with a higher density and is significantly more difficult to remove than rime [7,9,10].

2.2.3. Precipitation icing

Precipitation icing occurs when precipitation – either rain or snow – freezes after striking the surface. Wet snow can stick to a surface if the temperature is between 0 and 3 °C—a condition that ensures that the snow will have some liquid water present, allowing the snow crystals to bind together when they come into contact on the surface. While the binding strength of wet snow is often low when it first forms, it can become very hard if the temperature subsequently falls below 0 °C [2,5].

When rain falls at temperatures below 0 °C it leads to glaze, freezing rain, or drizzle. This often occurs in connection with a temperature inversion where cold air is trapped near the ground beneath a layer of warmer air [7,9,10]. This can also occur in the case of a rapid air temperature rise where an object's temperature is below freezing even though the air temperature is above freezing.

2.3. Ice accretion modeling

To aid in predicting the formation and effects of ice accretion some empirical and statistical models for the accretion of ice on turbine blades have been developed by the aerospace industry. These programs were developed to model the leading edge icing of aircraft wings, i.e. TURBICE and LEWICE [2]. Such packages utilize wind speed, temperature, accretion time, liquid water content and droplet size as input data then simulate the shape and amount of resulting ice on the aerofoil [2,9].

Wind tunnel tests can also be carried out using ''artificial'' iced profiles with various types and amounts of ice accretion to model accretion effects. This information can be used as input for models, which then predict load and power output for iced rotor blades [6]. Wind tunnels have also been used for the simulation of ice accretion on turbine blades.

2.3.1. Ice accretion profile

Typically, leading edges of rotor blades collect more ice than the rest of the blade profile because of the stagnation point in

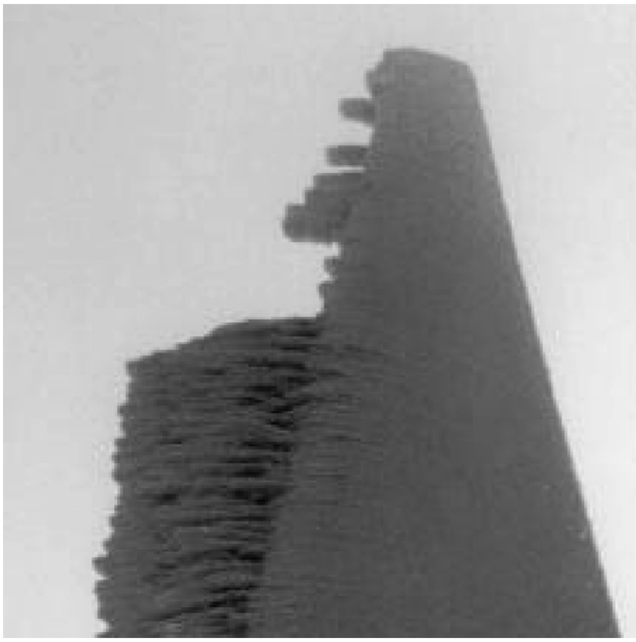

Fig. 2. Serrated ice accretion on turbine blade edge formed by an alternating series of ice breaking and reforming events; Tammelin [12].

the flow that exists there. Often, blades already carrying ice can take on a saw-tooth appearance; this is due to the aerodynamic forces that are sufficient to break ice fragments off, then subsequent ice accretions build until the leading edge takes on the serrated appearance shown in Fig. 2.

2.4. Current turbine blade icing solutions

In recent years, extensive research has been undertaken to identify and model ice prevention methods. Most of these methods are taken from the aviation industry and can be classified in two categories: active and passive. Passive methods rely on the physical properties of the blade to prevent ice accumulation while active methods rely on an external system applied to the blade. Two types of systems can be employed to prevent icing—specifically de-icing and anti-icing. The former removes the ice from the surface after its formation, while the latter prevents the initiation of icing [13]. These systems can be either passive or active and are described in the following sections.

2.4.1. Active methods

Active protection methods require supplied energy to perform, and include thermal, chemical, and pneumatic techniques and act as de-icing or anti-icing systems.

2.4.1.1. Active de-icing systems. Small aeroplanes often use mechanical de-icing systems—inflatable rubber boots on the leading edge of the wing that expand and contract on ice-prone areas of the aircraft. These systems have not proven pragmatic for wind turbine application for several reasons; obvious ones include the increased aerodynamic interference and noise that would be caused by an inflated boot. Further, the additional mechanical complexity associated with such a system would add significantly to the maintenance burden for the 20-year life span of the turbine [4].

2.4.1.2. Active anti-icing systems. Most active methods that have been developed at least to a prototype stage have been based on thermal systems that remove the ice by applying heat to the blade. Heating the blade's surface can be achieved through several methods:

- *Electrical resistance heating*. The electrical ice protection system consists of a heating membrane or element that is applied to the blade surface. The membrane or element is laminated into the blade structure. These thermal ice prevention systems are simple and have been used successfully in the aerospace industry for many years. Similar heating systems were developed for wind energy application in the mid-1990s [4]. At present, there are many commercially available electrical blade heating options. The Finnish blade heating system – carbon fibre elements mounted to the blades near the surface – has the widest operating experience with installation in 18 turbines at various sites with a total of nearly 100 operating winters [2]. A JE system of direct resistance heating has been shown to work effectively as well, but has not yet seen mass production [7].
- *Indirect heating of the surface*. This method heats the inside of the blade with warm air or a radiator, and the heat is conducted to the outer surface. Such a system has been installed on an Enercon turbine in Switzerland [14].
- *Microwave heating*. These systems are based on microwave energy technology, but have not yet to our knowledge, been successfully implemented [2].
- A system where the blade surface is protected by a layer of clean air has been conceived. This system utilizes air flow from inside the blade pushed through rows of small holes near the leading and trailing edges to generate a layer of clean and, if necessary, heated air directly around the blade surface. This layer of air would deflect the majority of water droplets in the air and would melt the few droplets that managed to strike the surface [14].

The following points highlight the inherent disadvantages connected with these heating methods:

- Leading edge heating elements will not help de-icing when active stall-controlled turbines are at a standstill (e.g. during icing conditions combined with low-wind speeds).
- Positioning the heating elements at the leading edge can also cause potential structural issues with the blades. Rotor rotation causes high deterministic loads on the blade's structure. Further to this, the aerodynamic driving forces and superposed edgewise vibrations, caused by a low damping of the natural frequency in this direction, are added to the gravity loads. Consequently, high stress in the load carrying girder of many glass reinforced blades leads to even higher stress in the wires or fibres of the heating elements. This is particularly true when the heating elements are made from

carbon fibre—whose Young's modulus is much higher when compared to the glass fibres of today's rotor blade structures. In other words, the ''heating fibres'' end up bearing a large portion of the loads. Special technical solutions are required in order to avoid these effects and prevent cracks in the heating elements [4].

- The electrical heating elements – metal or carbon fibre – can attract lightning strikes at an exposed site.
- The airfoil contour must be kept free from waviness to avoid unnecessary disturbances of the laminar flow around the leading edge during ice-free conditions. Electrical fibres and laminate embedding may increase surface roughness [4].
- For blade cavity forced warm air thermal systems, the efficiency of the system wanes as turbine blades increase in size; shell structures become thicker and thermal resistance rises. In practice, this means that very high temperatures are needed inside the blades to keep the outer surfaces free of ice, even in mild conditions. Considering the maximum operating temperatures of thermoset composites, using such temperatures inside the blade structure to keep the blades free of ice would be a significant challenge [14,15].
- Should one blade heater fail, a significant mass imbalance may be imposed on the rotor as each blade may have different icing loads; such a situation occurred for Yukon Energy in 1996 [15].
- In some cases, the run-back water on the blade during icing and blade heating can freeze after it passes the heated area. Ice formed from run-back water has a high density and may be dangerous when shed from the blades in big pieces. It can also accumulate at positions where it may be aerodynamically harmful [15].
- Current anti-icing technology consumes electricity. The break-even cost of such a heating system depends on how much energy production is lost due to icing and the price of electricity. Therefore, when the financial benefits of a blade heating system are evaluated—icing time, severity of icing, and potential wind resources need to be known. Based on early work in Europe, thermal anti-icing requires power equal to at least 25% of the turbine's maximum power. Recent work conducted in Europe, however, indicated that the early estimates in anti-icing power requirement can be revised down. Current claims suggest that the power requirement ranges between 6 and 12% of the output for smaller commercial scale turbines [6].

2.4.2. Passive methods

Passive methods take advantage of the physical properties of the blade surface to eliminate or prevent ice, and are similar to active methods in their ability to act as de-icing or anti-icing systems.

2.4.2.1. Passive de-icing systems

- A system designed with blades flexible enough to crack the ice loose has been proposed, as blade flexing is already known to help shed the ice, to our knowledge there is little published information on this subject. The disadvantage of trying to crack the ice loose is that thin layers of ice can adhere quite strongly to the blade and may not be brittle enough to crack loose from just the vibration of the blade; it would likely also compromise the aerodynamic properties of the blade [14].
- An electro-expulsive system that depends on very rapid, electromagnetically induced vibrations has recently been certified for use on Raytheon's Premier I business jet. This system holds promise for smaller, new, general aviation airplanes but there remains a lack of practical information for wind turbines [16].
- Other passive systems such as active pitching of the blades, start stop cycles and facing the blades into the sun are used to remove ice from turbine blades. Though these methods may work in light icing environments, few studies have been published to validate their efficacy, and such methods may damage the turbine and/or reduce power production [17].

2.4.2.2. Passive anti-icing systems

- In 1996, Yukon Energy ''painted'' their blades with a black coloured coating called StaClean® [15]. StaClean® is purported by the manufacturer to be non-wetting, slicker than Teflon®, highly impact and abrasion resistant. Such qualities would be very advantageous in minimizing ice accretion. Subsequently this was reported to be effective at reducing icing issues [18]. Though, the black colour did not significantly increase blade surface temperatures during winter months [19]. In fact in many instances the sections of the blade coated only with the manufacturer's original gel-coat actually rose to a marginally higher temperature than sections coated with the black StaClean®.

Special coatings that reduce the shear forces between the ice and the blade's surface are not new; as icing is a substantial problem for aircrafts as well. While development of an ideal surface coating for icing mitigation still eludes the aerospace and wind turbine industry, it remains the only method among those discussed herein that may prevent the adhesion of insects and the erosion of the leading edge.

3. Effects of insect contamination

Stall control is not very accurate in practical application, and many stall-controlled turbines do not meet their specifications [20]. The power of wind turbines operating in high winds has been known to drop for no known reason, causing production losses from 25 to 50%—a phenomenon referred to as a 'Double Stall' or a 'Multiple Stall' [20]. Corten et al. [20–22] attributed this multiple power level occurrence to the insect theory, which states that these levels correspond to different degrees of insect contamination. Fig. 3 illustrates an example of a wind turbine blade contaminated by insects. A low contamination level decreases the power by 8% of the design value; while at high levels it can be decreased by up to 55%. In this study a device called a 'stall flag' was employed—a hinged flap that opens up in a separated airflow to uncover an individual reflector. Employing a projector as a light source, they measured the separated flow from the intensity of reflected light.

Fig. 3. Insect collisions foul the leading edge of wind turbine blade (M.D. Burns/Oak Creek Energy Sys.).

The hypothesis has been validated by three crucial experiments—the observation of the decrease of the stall angle due to contamination, monitoring the progress of the power level over time that showed a decrease after each period of low wind, and the application of artificial roughness to turbine blades, which prompted the power curve to drop in a way that mirrored the multiple power level observations. Insects prefer to fly in conditions of high air humidity, low wind and temperatures above about 10 °C. Under these circumstances, they will increasingly foul the leading edges of the blades.

Efficient aerodynamic performance is best achieved when the airflow is attached to the aerofoil section. Flow separation can take place under a high angle of attack or due to the presence of roughness near the leading edge. In the latter case, the primary flow detaches from the airfoil at a point called the separation point, and beyond this point the airflow near the aerofoil actually proceeds away from the primary flow direction—a state called reversed flow or separated flow. Generally, such flow separation is detrimental to the performance of the aerofoil and should be avoided [23].

Insects rarely fly in high winds, so turbines operating in "steady" high-wind conditions do not become contaminated, and their power levels remain constant. Although, with high winds, the angle between the flow and the blades increases and the aerodynamic suction peak (the area of minimum pressure and maximum air velocity) shifts to the leading edge; and if the leading edge is already coated with dead insects (from a low-wind period), the resulting power output will fall. The greater the contamination at the suction peak, the sooner the blades will stall and the more lift will be lost. Thus after each period of low wind, the amount of insect contamination may change and cause a different power level to be produced in high wind [20–22].

3.1. Current solutions for insects

The most common solution for reducing the effect of insects and air pollutants on the blades is to wait for rainfall to wash the blades. There are some services that offer cleaning machines that can be hoisted up and down the blades—cleaning and polishing the blades like a car wash tunnel. The disadvantage of this system is that the wind turbine must be stopped, so the resulting power loss will simply add to the losses created by the insects [24]. Another blade washing technique involves pumping water up through the tower and spraying it into the wind and through the blade tip—a solution that can be implemented while the turbine is in operation [25].

The compromise of the aerodynamic efficacy through insect fouling is a result of the increasing surface roughness. In the past, airfoils had been more susceptible to the effects of roughness. Recently, improved families of airfoils designed specifically for horizontal-axis wind turbines have been patented, wherein the airfoil's maximum lift coefficient is designed to be largely insensitive to leading edge roughness [26].

Of the options discussed, the most appropriate means of insect adhesion prevention may be through the application of non-stick coatings that alleviate the adhesion by providing a low-friction, low surface free energy and smooth surface on which insects have great difficulty settling. Even if settling does eventually occur on the surface, the bonding between the foulants and the surface would be so weak that the shear forces on the airfoil may easily remove them.

4. Effects of erosion

Wind carrying large amounts of sand and water droplets can erode the leading edge of a turbine blade and increase surface roughness. These effects deteriorate aerodynamic performance and reduce machine power output in the same manner as insect contamination. The potential for erosion depends on the force at which the particulate matter impacts the airfoil. Geometric shapes and the relative velocities of both the airfoil and the impacting particle determine the impact force of the particulates. Wind speed and rotational speed of the blade determine impact velocity. The rotational speed of the blade is at its maximum at the outboard tip of the airfoil, which is the furthest from the rotational axis [27].

According to van Rooij and Timmer [28] the effect of roughness on a blade's aerodynamic performance depends on the geometric design of the blade, such that a blade may be adapted to induce minimal energy loss. However, surface roughness changes during operation due to contamination (insects) or erosion, and will typically always lead to unpredicted energy losses.

4.1. Current solutions for erosion

The common technique for improving an airfoil's erosion resistance is to apply an elastometric material to the leading edge of the airfoil in the form of a tape. These tapes must be replaced frequently however; since they fail to adequately absorb the impact energy of the particulate matter. On the other hand, these tapes are suitable for small turbines, though they will increase the aerodynamic drag on the blade surface [29].

For example, the 7.5 kW Bergey EXCEL-R wind turbine blades are protected from erosion with a special polyurethane leading edge tape and the blades are painted with an aircraft-quality polyurethane paint [30].

There are other innovations that are worth noting, despite the fact that they are not yet commonly available. One is the vacuum infusion of large thermoplastic composite blades, which show higher resistance against erosion for areas like the leading edge and blade tip [31]. Another is the application of a nanocomposite layer to the leading edge of an airfoil [27]. Adding the nano-sized reinforcing particles to an elastomer allows the nanocomposite to absorb the impact energy over a larger volume when compared to a pure elastomeric material.

5. Potential surface engineering research directions for each of icing, insect fouling, and blade surface erosion

Novel surface engineering applied to blade surfaces has been identified here as a versatile solution that potentially addresses the majority of the aforementioned problems. In order to further investigate the effect of surface engineering, the physical or mechanical properties of surfaces that have low ice adhesion, anti-stick and erosion resistance properties must first be understood. These properties are described in the following sections.

5.1. The physics of ice adhesion

Using special coatings to reduce ice adhesion requires a comprehensive understanding of the fundamental physics involved. The physical process of adhesion can be attributed to three different kinds of bonds. First is covalent or chemical binding, which holds atoms in molecules together and acts only over distances of the order of 0.1–0.2 nm. For most of the materials – particularly the blade material – there is no affinity between water molecules and the surface. The second type of bonds is due to Lifshitz–van der Waals forces, which have no considerable effect on adhesion. It is electrostatic forces between two solids which contain non-compensated spatial distributions of charge that can contribute most to the adhesion [32].

Exerting an external force on the ice-solid interface can lead to cohesive breaks (breaks that happen within the ice) or adhesive breaks (breaks that happen in the ice-solid interface and occur when the strength of adhesion is lower than the ice strength). The strength of adhesion between two materials is defined as the free energy required to separate a boundary of unit area between the materials, i.e. the work of adhesion:

$$W_A = \gamma_1 + \gamma_2 - \gamma_{12} \tag{2}$$

where γ_1, γ_2 and γ_{12} are the surface energies per unit area of materials 1, 2 and the interface, respectively. Work of adhesion for liquid–solid interfaces can be described as a function of the angle of contact, θ and the surface free energy between liquid and vapour, γ_{lv}:

$$W_A = \gamma_{lv}(1 + \cos\theta) \tag{3}$$

Since the binding energies of H_2O molecules and different solids are expected to be similar in ice and water, it may be supposed that the values of W_A on different ice-solid interfaces will be a function of wetting angle of water on these solids. Petrenko and Whitworth [33] collected measurements made by other investigators and concluded that there is a correlation between angle of contact and adhesion strength, although its deviation is high [33]. The results of NASA LEWICE and BF Goodrich studies also indicate that hydrophobicity does not necessarily produce poor ice adhesion, but shows that hydrophilic materials have in fact substantial ice-adhesive properties [34,35]. The following items contribute to the poor correlation between ice adhesion and contact angle:

- The plastic deformation that is associated with fracture on the interface will absorb energy, so the assumption that the force required for adhesive failure depends only on W_A takes no account of this energy.
- The electrostatic component of W_A is different for water and ice, unlike the previous assumption [33].

There are many parameters that affect the adhesion strength of ice to surfaces; unfortunately most of them are not well understood. Some of these parameters are mentioned as follows.

5.1.1. Effect of temperature on ice adhesion

Scavuzzo et al. mentioned that decreasing temperature between 0 and −4 °C will increase ice adhesion strength, but at this temperature ice adhesion reaches its maximum and further temperature reduction will not have an effect on adhesion [34]. The results of shear tests between stainless steel and ice in the form of frozen snow show that the shear strength increases with falling temperatures as low as −13 °C, at which point the adhesive strength of ice becomes higher than its cohesive strength—therefore at lower temperatures failure occurs within the ice and decreasing temperature will have no effect on shear strength [36]. Alternatively, adhesion of ice to some plastics (PTFE, polystyrene, perplex and a thick layer of stearic acid) were found to be independent of temperature [37].

5.1.2. Effect of surface roughness on ice adhesion

Increasing surface roughness can boost the shear strength by a factor of 10 from a mirror polished surface to a machined one [32].

5.1.3. Effect of surface contamination on ice adhesion

The presence of a contaminant film or particle will decrease the area to which the ice adheres strongly and adhesion strength will be reduced, though these contaminants can act as ice nucleating points and increase ice accumulation [37].

5.1.4. Effect of type of ice on ice adhesion

It is reported that the adhesive shear strength of rime ice is much weaker than that of glaze ice [34]. In order to measure the adhesion strength of ice to different coatings, and to introduce a material, the tests must be performed with atomically clean and

flat surfaces under a constant climate condition. The results of some of the tests performed to evaluate the ice adhesion properties of materials are mentioned in Section 5.4.

5.2. Physics of an anti-stick surface

In order to increase the anti-stick properties of a substrate, its surface energy, friction coefficient and roughness must be decreased. If there is a relation between anti-icing and ice-phobic properties, applying an ice-phobic coating will satisfy the anti-stick requirements as well.

5.3. Physics of an erosion resistant surface

Material removal during erosion depends on the properties of the target material, the physical and chemical characteristics of erodent particles and the exposure condition. With respect to the impact angle, solid particles erosion falls into two categories:

- Erosion at normal impact angles ($\alpha \approx 90^\circ$)
- Erosion at oblique impact angles ($0^\circ < \alpha < 90^\circ$)

Generally two modes of ductile and brittle erosion are observed, neither of which directly match the traditional grouping of materials according to their failure [37]. In ductile mode, weight loss due to erosion has a maximum at low impingement angles while in brittle mode, the maximum is at high impact angles ($\alpha \approx 90^\circ$).

Elastomers and ductile polymers generally exhibit ductile erosion behavior, but elastomers present a much lower weight loss compared to that observed for ductile thermoplastics. This difference in behavior can be traced to the mechanism by which material removal happens—tearing and fatigue for rubbers, cutting and chip formation for ductile metals and polymers and brittle fracture for brittle polymers. The phenomena that occur during turbine blade erosion fall into two categories:

- Normal, elastic/plastic impact
- Oblique, elastic/plastic impact

5.3.1. Normal, elastic/plastic impact

This type of impact is most frequent, here the impact energy converts to plastic energy and heat (by internal friction) with the latter displaying a larger proportion. Increasing the ductility of impact partners will increase the number of stress cycles to failure—thereby decreasing erosive wear. In the case of elastomers, a much lower amount of kinetic energy will be absorbed on impact. Elastomer failure is attributed to their Possion's ratio (0.5). The surface tensile stresses arising from frictional forces cause fine cracks to grow progressively in the surface—consequently decreasing the friction coefficient and alleviating the erosion rate [38,39].

5.3.2. Oblique, elastic/plastic impact

At lower impact angles, the parallel component of velocity to the surface becomes higher and micro-cutting and micro-ploughing mechanisms (which are related to the relative hardness of impact partners) start playing a role. This is the reason for the higher erosion rate of the ductile matrix at lower impact angles, while brittle materials are not so easily cut by particles and therefore have a lower erosion rate at lower impact angles. Elastomers eroded at glancing incidence show formation of tears and cracks perpendicular to the erosion direction. Impact particles slide on the surfaces, producing deforming ridges at the first stages of erosion and causing the growth of fatigue cracks from the base of each ridge [38].

While the erosive wear mechanisms that can take place in polymer materials are different, there is no definition for the anti-erosive properties of these materials. A large number of factors affect the erosion resistance of a polymer including the crystallinity, physical and chemical network characteristics, thermal conductivity, glass transition temperature, mechanical properties (such as hardness, tensile strength, modulus of elasticity, fracture toughness, yield stress, rebound resilience, friction coefficient, ultimate strength and elongation) and the degree of work hardening and softening by heat generation. None of these factors have a common effect on polymers, which can be attributed to high strain rates in the impact of erosive particles and the change in some of these properties during erosion, such as the friction coefficient and hardness.

A number of models have been proposed to relate the abrasive wear resistance of polymers to other mechanical properties. One of the earliest of these is commonly known as the Ratner–Lancaster correlation [39], and it predicts that the wear coefficient is inversely proportional to the product of stress and strain at tensile break, this is an estimate of the energy to fracture. Another model by Friedrich [40] proposes that the brittle index in the form of H/G_{Ic}, where G_{Ic} is the fracture energy and H is the hardness, this is an indicator of erosion resistance. Nevertheless, Budinski [41] studied these models for 21 plastics/elastomers and found poor correlation between experimental data and these models.

It follows that materials with anti-erosive properties ought to be extremely hard and tough such that the impacting particle is unable to make any impression on the surface. Conversely however, the material should also be highly elastic so that the kinetic energy of the particle is harmlessly dissipated. Thus, no general statement for erosion properties of polymers can be easily made without additional research focused on revealing the appropriate combination of properties necessary for a material to be deemed truly anti-erosive.

5.4. Potential coating candidates

A wide range of coatings claiming anti-icing properties have been tested by NASA LEWICE and BF Goodrich research centers, including a hydrophobic treatment for aircraft windshields (PPG Surface Seal), a Dow Chemical "Anti-Stick" developed water-based fluorocarbon, a second Dow coating, Freedom Ceram-Kote MTM and a commercial ceramic-epoxy coating used in petroleum, marine and sewage applications to protect against corrosion and erosion. Only the Dow Anti-Stick appeared to reduce the adhesion of ice when compared with the

uncoated surface. Perhaps the most interesting result of these tests was the discovery that Teflon provided no reduction in adhesion. This could be assumed to be due to its high pore density, which probably encouraged strong mechanical bonding with ice [34]. Meanwhile, in research performed on a group of thermoplastics and coatings to reduce ice accretion on Corps hydropolymer, including Avetal, Derlin, Teflon, UHMWPE, PSX-700, Inerta and Envelon; the highest reduction in ice accretion was observed with Teflon [42].

One of the most common materials with an ice-phobic claim are silicon–epoxy-based resins in which the silicon part provides the low ice adhesion properties and the epoxy part provides the erosion and impact properties [43]. Claims have also been made regarding their resistance to erosion and fouling, but these claims have yet to be conclusively substantiated.

Current research is heading towards nanocomposite coatings, polymers reinforced by minute, nanometre-scale particles. This is because nanocomposites create very high contact angles with water and the reinforced polymer acts to absorb and dissipate the higher impact energy caused by the repeated impact of particulate matter, which produces higher erosion resistance. One particular type of nanocomposite has been proposed that benefits from electrically conductive particles that can be used to raise the temperature of surface it coats [44]. Another proposed coating is a molecular combination of organic and inorganic constituents. According to TPL Inc., the inorganic component will impart hardness and durability while the organic part will impart flexibility and icephobicity [45]. Another proposed material is a liquid and/or solid anti-icing filler and/or oil that are combined with erosion resistant silicone and/or fluorocarbon elastomeric materials to create erosion resistant anti-icing coatings [46]. A mixture of Rain-X and MP55 PTFE (powder Teflon) has also been claimed to be an outstanding coating to reduce ice adhesion to surface of the space shuttle [47]. An anti-icing coating has also been developed in Cape Cod Research, Inc. for navy applications called PCM-based icephobic coatings [48]. Presently, detailed information for most of these coatings remain proprietary, consequently most of the data sheets and chemical compositions are classified and unattainable.

6. Conclusions

Ice, insects, and erosion represent significant economic issues for commercial wind turbine operation, as they can decrease the aerodynamic efficiency of wind turbine blades, provoke sudden shutdowns, and contribute to unscheduled maintenance requirements. The significance of these concerns will likely increase as more turbines are being located in frontier climates to take advantage of higher wind velocities and/or densities.

The development of a single holistic solution to the problematic surface engineering issues facing commercial wind turbines is a formidable undertaking. The multidisciplinary nature of the research may reveal the reason for relative paucity of literature that relates the three major issues together. We have attempted to summarize the detailed difficulties that each issue produces for the industry. Further we have compiled many of the currently available solutions that have been reported, and have attempted to bring to light some relevant considerations for future research on this topic, and in this process have arrived at some general conclusions.

1. Neither passive nor active measures against icing have proven completely effective in preventing initial icing and subsequent ice accretion.
2. As active measures against icing (or insects) represent a significant initial capital investment, and still require subsequent power to operate, resources might be better devoted to the development of a passive solution capable of providing some resolution to each of ice, insects, and erosion.
3. A single application coating material could provide a multipurpose solution that may at least reduce the frequency of unscheduled shutdowns and maintenance issues.
4. Promising directions for future coatings research include further testing of silicon–epoxy-based resins for their ice-adhesive properties, and the continued development of new nanocomposites and combined organic/inorganic constituent materials.

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